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Gear Equipment of DSIF Antennas

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PASADENA, CALIFORNIA

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ABSTRACT

The large steerable ground antennas of the Deep Space Instrumentation Facility (DSIF) are briefly discussed. The current design of gear drives for the Az-El and Ha-Dec antennas at Goldstone Tracking Station is described, and drawings are presented to illustrate the comparison between commercial and modified configurations in this application. A statement of generalized system specifications for a large servo-drive gear set includes the following requirements: (1) high output stiffness and low input compliance, (2) low input inertia, and (3) reasonable stiffness/dollar cost. Use of the comprehensive parameter *Intrinsic Natural Frequency* in engineering analysis of a gear set is explained, and formulas are presented for application of this parameter in gear design.

I. INTRODUCTION

In the large steerable ground antennas of the Deep Space Instrumentation Facility (DSIF),[1] the gear drives are components of vital importance. It is the purpose of this paper to describe briefly the design of the existing DSIF gear drives, and to present general parameters of significance in the design of similar large servo drives.

The primary objective of DSIF is to provide the tracking, communications, and data-gathering capability required to support lunar, planetary, and deep-space missions for NASA. The DSIF net consists of three operational stations, located in areas about 120 deg longitude

[1]The DSIF Program is managed by the Jet Propulsion Laboratory, California Institute of Technology, under National Aeronautics and Space Administration Contract No. NAS 7-100.

apart. One station is at Goldstone, Fort Irwin, about 50 miles north of Barstow, California. The others are in Johannesburg, South Africa, and Woomera, Australia.

The primary communication element of each station is a paraboloidal reflector of the polar-axis-mounted type, 85 ft in diameter, and steerable in hour-angle and declination by relatively large-diameter multiple-pinion gear sets on each axis. The polar-axis mount is directly similar to the mount used in astronomical telescopes, in which a polar axis is parallel to the Earth's axis. A second axis, at a right angle to the polar axis, is used for scanning in declination. This type of mount is customarily identified by the acronym Ha-Dec, the abbreviation for Hour-angle–Declination. There are two of these antennas at Goldstone (Fig. 1) and one at each of the other two stations.

In addition, there is an 85-ft-diameter Az-El-mount antenna at Goldstone (Fig. 2), which will be used for high-power command capability and also as a research and development facility where experimental work will include investigations of planetary radar. The Az-El mount consists of a vertical axis, rotatable in azimuth, supporting a movable alidade (or yoke) support member, upon which the reflector is journaled in elevation. The acronym Az-El denotes the abbreviation for Azimuth-Elevation.

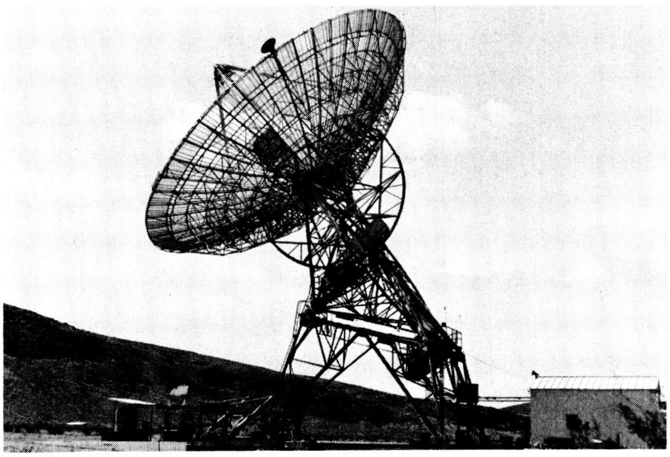


Fig. 1. Ha-Dec antenna, Goldstone Tracking Station

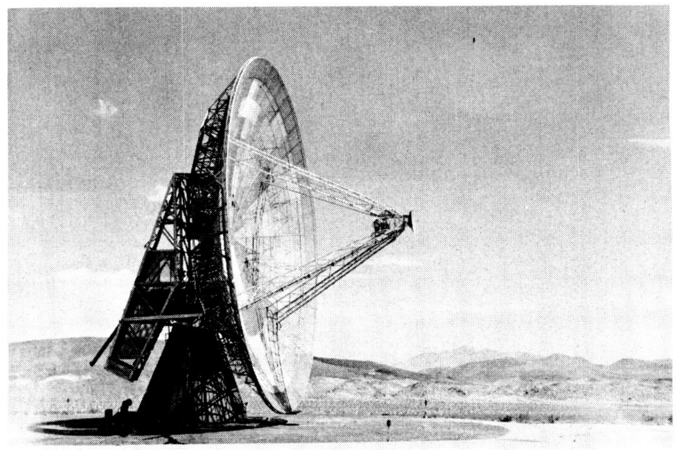


Fig. 2. Az-El antenna, Goldstone Tracking Station

II. CURRENT DESIGN OF GEAR DRIVES FOR DSIF ANTENNAS

Both types of antennas use multiple-pinion drives, counter-torqued against each other at low torque levels to eliminate backlash. The drives are multiple-ratio clutch-selected hydraulic servos, employing hydrostatic servo valves, and having a nominal input of 75 hp for the Ha-Dec mount and 200 hp for the Az-El.

The Az-El mount requires more horsepower input for equivalent tracking performance because of "gimbal lock" near the zenith, whereby the azimuth axis must accelerate to about 35 times the sidereal rate for sidereal targets 1½ deg toward the equator from the zenith (i.e., the target declination is 1½ deg less than the station latitude).

In actual practice, both mounts are required to provide smooth tracking rates from about one-half sidereal, or about 0.002 deg/sec, up to reasonable slew speeds of 1 deg/sec for Ha-Dec to 4 deg/sec for Az-El, or equivalent speed ratios of 500:1 and 2000:1, respectively. A wider speed range on the low-speed side would be more desirable, but conventional hydraulic servo drives, even in the two-speed-ratio types, have difficulty in this regard.

The Ha-Dec antennas display a calibratable system tracking accuracy of about ± 0.02 to 0.03 deg (1σ), and the Az-El a somewhat lesser accuracy. This compares, approximately, to a 0.9-deg ½-power beamwidth at 960 Mc.

Both antennas must operate in winds as high as 45 to 60 mph, and this requirement imposes a high torque loading on the positioning gears. Above these wind levels, the antennas are moved to a minimum-aerodynamic-moment attitude and stowed. The equivalent design tooth working load is up to 50,000 lb per tooth on the polar gear, and less on the others.

Figure 3 presents a photograph of the Az-El servo-drive gear-box assembly, taken at the Falk Corporation factory prior to installation at Goldstone. Other design details of the Az-El and Ha-Dec gear drives are illustrated in Figs. 4 to 6. In Fig. 7, one view is taken from the Az-El gear-box assembly drawing (Fig. 3) and shown in direct comparison with the original commercial design before modification.

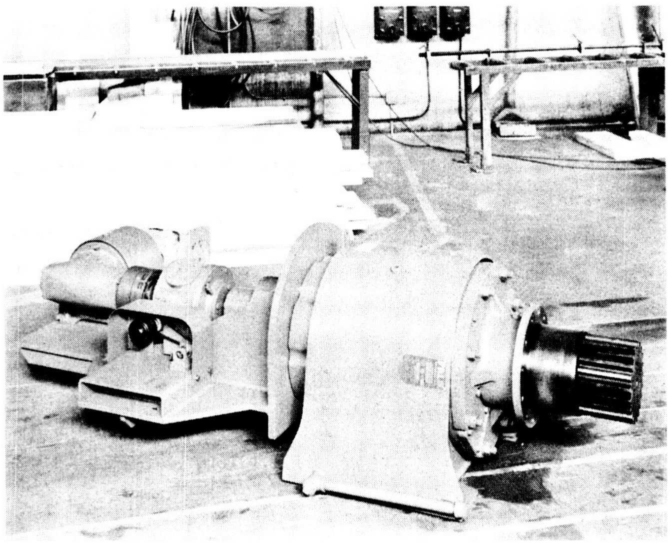


Fig. 3. Az-El servo-drive gear box (photograph taken at Falk Corporation factory prior to shipment, and used with permission)

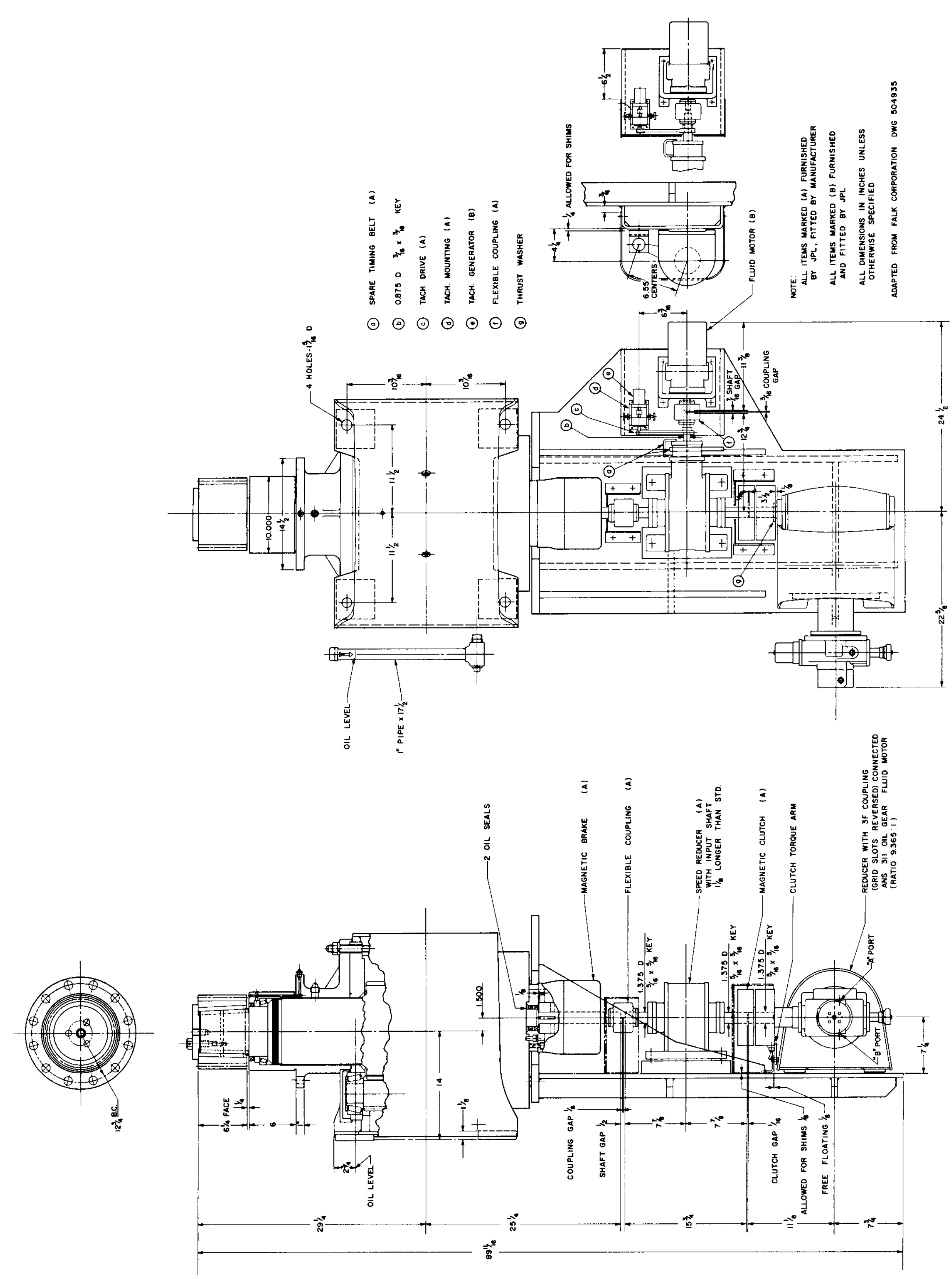


Fig. 4. Assembly drawing of Az-El servo-drive gear box (sketch adapted from Falk Corporation Dwg. 504935, and used with permission)

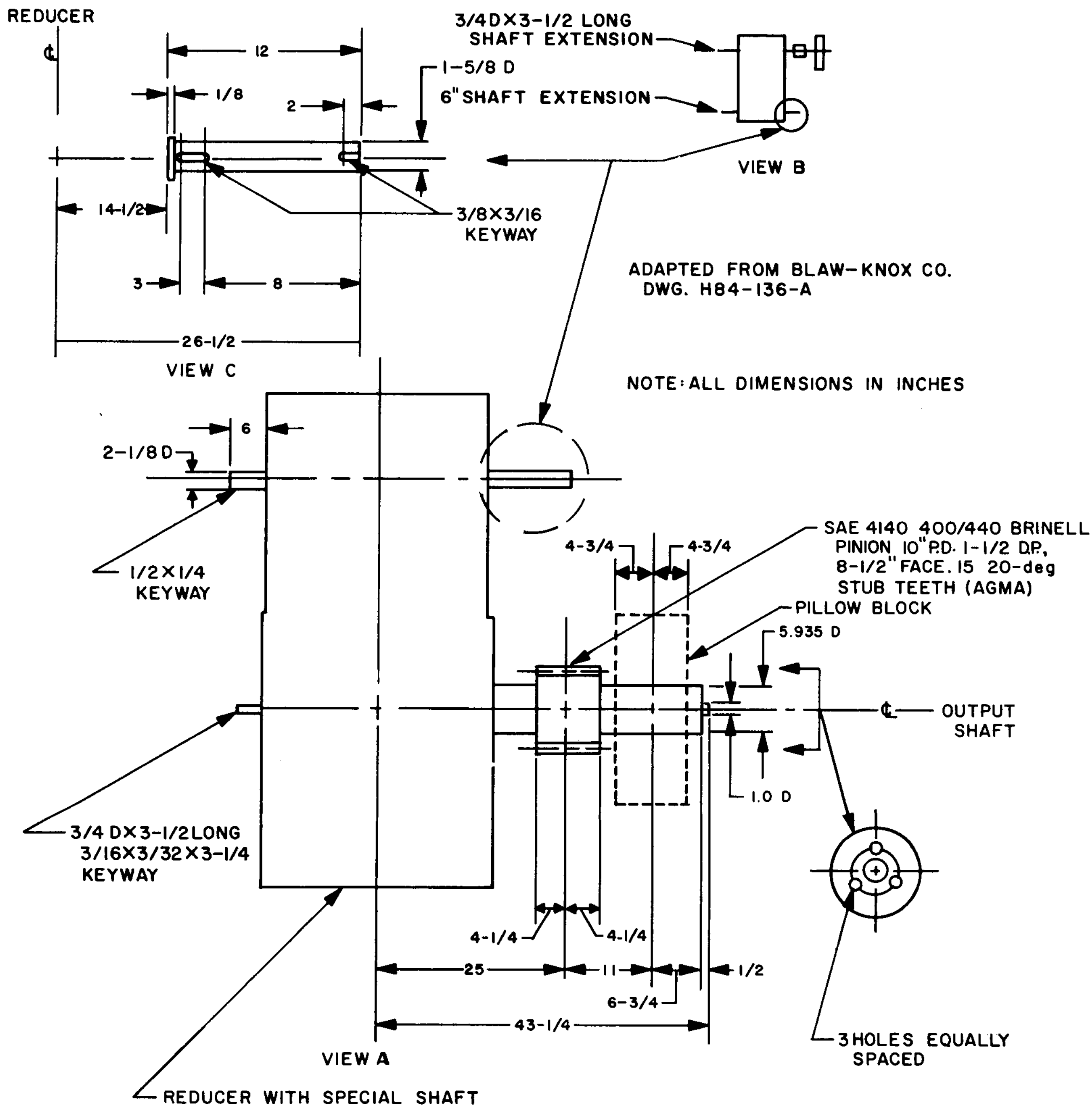


Fig. 5. Ha-Dec polar-drive gear box (sketch adapted from Blaw-Knox Company Dwg. H84-136-A, and used with permission)

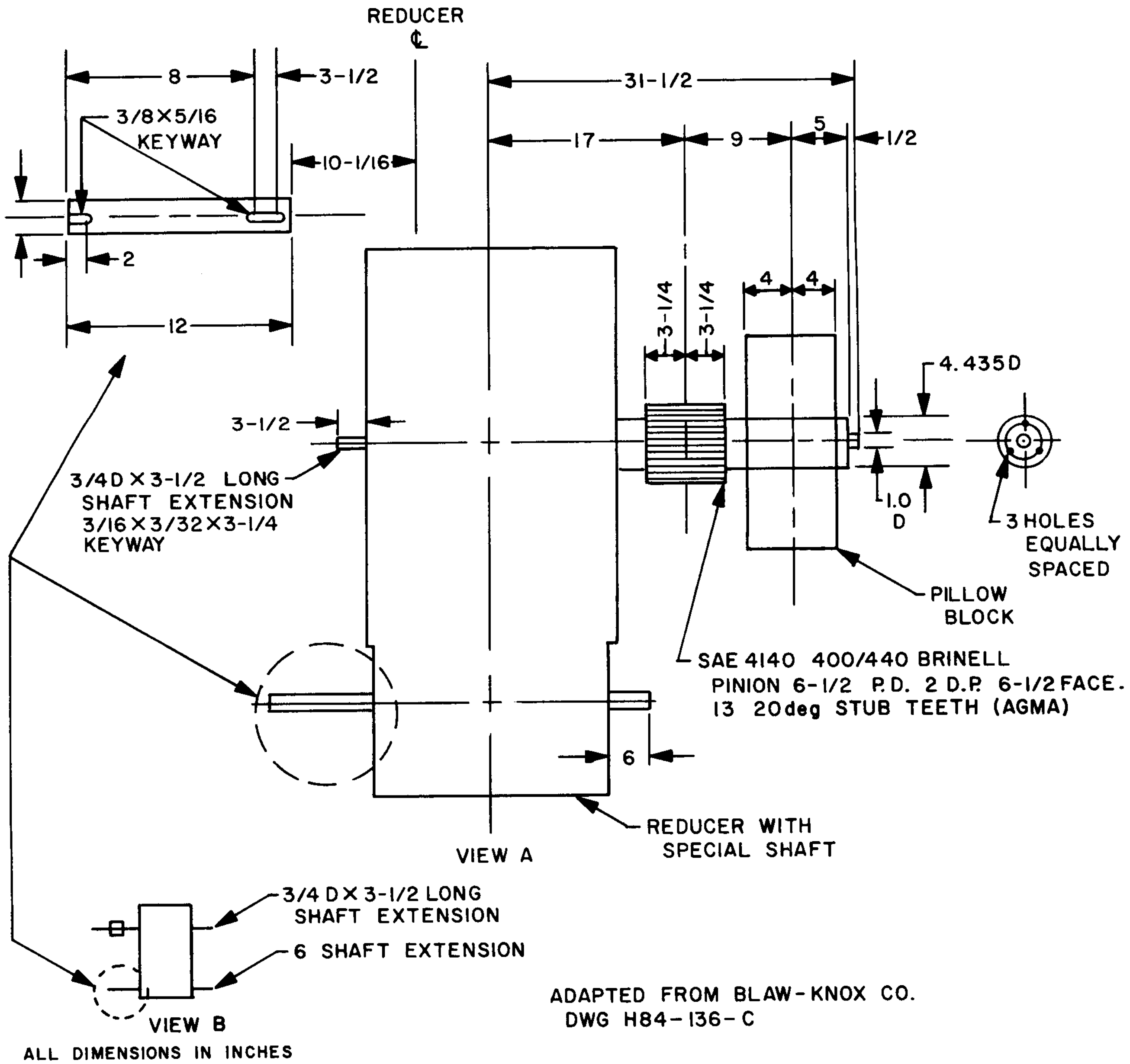
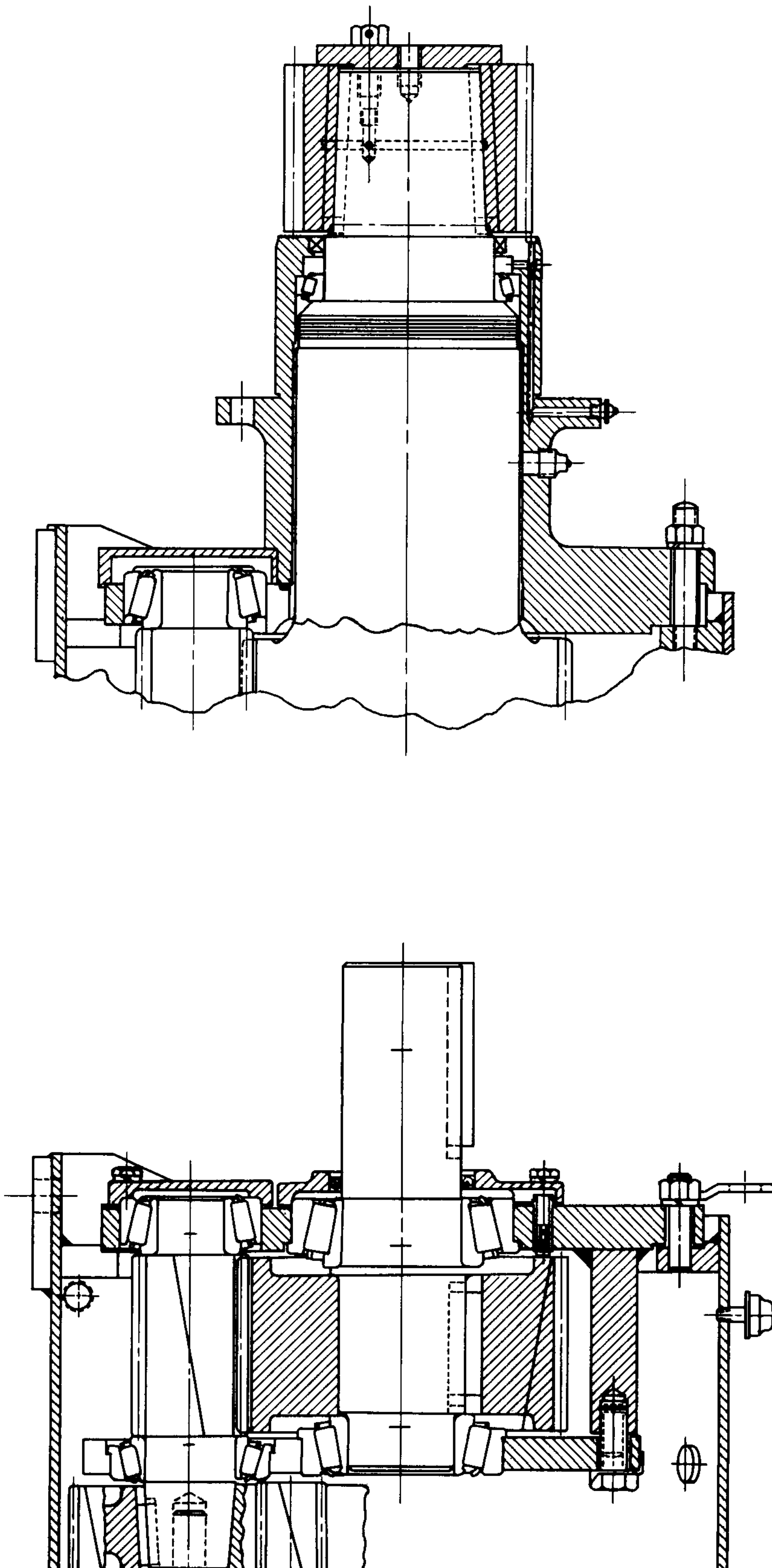


Fig. 6. Ha-Dec declination gear box (sketch adapted from Blaw-Knox Company Dwg. H84-136-C, and used with permission)



VIEW A. COMMERCIAL DESIGN
BEFORE MODIFICATION

VIEW B. MODIFIED DESIGN
FOR INCREASED STIFFNESS

Fig. 7. Comparison of original and modified configurations for Az-El gear box (sketch adapted from Falk Corporation Dwgs. 504466 and 504935, and used with permission)

III. SIGNIFICANT DESIGN PARAMETERS FOR LARGE SERVO DRIVES

In the following paragraphs, a discussion is presented of some design aspects which are of significance in determining the suitability of a gear set for use in large servo drives of this type.

Apart from the usual considerations of mechanical strength, surface finish, tooth form, resistance to wear, etc., the most important general implication of the gearing is its effect on the dynamic characteristics of the antenna system.

Thus, a generalized system specification for a large servo-drive gear set may be enunciated as follows:

1. The gear set should have high output stiffness to load-perturbing forces, low input compliance, and low backlash. It must withstand rapidly reversing peak-impact design loads on an intermittent servo-test basis and normally reversing servo loads on a continuous-operation basis.
2. It should have low input inertia, so as not to degrade servo-driver acceleration performance.
3. It should be obtainable at reasonable cost.

A. *High Output Stiffness and Low Input Compliance*

The purpose of the gearing is to couple the servo motors to the actual antenna structure, to move the structure as exactly as possible, and to prevent wind and friction movements from disturbing the accuracy of this command action. Hence, one of the most important properties of a gear set designed for this purpose is the stiffness with which the gear set positions the antenna against the disturbing wind, friction, and acceleration forces. This usually indicates large pinion shafts, outboard bearings, all loads carried in shear rather than bending, and an oversize integral pinion-gear and shaft, with close-coupled gears and spread bearings centered in supporting case diaphragms. The bearings on the ouput shaft in particular, and other shafts in general, should be designed and supported for minimum bending and load deflections.

This requirement for high output stiffness *cannot* usually be met by commercially designed hardware without rather drastic design changes. An example of this fact is the evolution in the Falk 8KZ4 boxes used for the azimuth drive of the 85-ft Az-El antenna. The modified output-shaft configuration, which is almost 4 times stiffer than in the original design, is shown in Fig. 7.

Since a high-performance servo drive essentially applies a rapidly alternating series of forward-reverse impact impulses to the drive gear when causing the antenna to follow a closely prescribed orbit in space-time, it follows that the input deflection of the gear set under load should be small. The servo engineer describes this requirement by the statement: "The input compliance of the gear set should be as small as is practicable." The compliance parameter is the reciprocal of the gear set's spring-constant property.

In a gear set with small compliance, the servo driver is required to rotate through only a small angle in order to exert full reverse torque; hence, it can "set on" the load very rapidly and can maintain very accurate dynamic pointing of the antenna.

The attainment of this desirable low-input-compliance condition in a large antenna system is one of the most difficult and agonizing system-engineering "trade-offs" imaginable. Let us examine some of the implications involved in this trade-off.

In order to decrease the compliance of a gear set, the size of all elements of the assembly might be increased. This procedure rapidly prices the gear drive to the point of unsatisfactory system–price balance. Moreover, as tooth size increases, usual manufacturing tolerances dictate greater backlash allowance on the output-end gear meshes. This appears as a larger dead zone on the servo input shaft, which is more undesirable than the compliance eliminated by the size increase, since backlash is a nonlinear discontinuous effect.

Large structures of this type have large internal deflections with temperature changes. The polar gear of the Ha-Dec, when set up for minimum gear-pinion clearance at high summer temperatures, has been observed to have approximately ¼-in. pitchline backlash (60 to 120 revolutions at the low-speed servo-motor input shaft) during low winter temperatures.

Furthermore, large structures of this type have large compliance in gears and gear-set mounts. This compliance appears as an effective shunt, which degrades the intrinsic stiffness of the gear set.

When two or more drive gears are counter-torqued against each other to eliminate backlash, the stiffnesses of the drives cannot be added together to obtain equivalent gear-set-system stiffness, apparently because perfect load sharing of servo drives cannot be achieved.

B. *Low Input Inertia*

The requirement for low input inertia is obvious. The available torque of the servo motor can be used for (1) overcoming the wind and inertia load of the antennas, and (2) accelerating the input members of the gear box. Straightforward engineering considerations indicate that the second type of torque utilization should be minimized as much as possible.

C. *Reasonable Cost*

In regard to cost, it appears that maximum stiffness per dollar is obtained with the minimum number of pinion-drive sets that will meet operational system strength requirements.

Thus, in descending stiffness/dollar ranking, we have the following general gear-set configurations:

1. One large circular-pitch gear and one large pinion, if system accuracy and backlash requirements can be met by no-antibacklash provisions (unfortunately, almost never the case).

2. One large-pitch gear and two large pinions, if anti-backlash provisions are mandatory.

3. One smaller circular-pitch gear and $2n$ pinions, if structural symmetry requires more than two pinion-drive points. Here, n is any small integer larger than 1, appropriate to system configuration. Antibacklash counter-torque is best applied in symmetrical pairs.

4. Two smaller circular-pitch gears, 4 to $4n$ pinions, if structural symmetry requires more than one large drive gear.

IV. INTRINSIC NATURAL FREQUENCY

Another tool required in engineering analysis of a gear-drive system is a parameter closely indicative of the gear set's dynamic effectiveness in the complete servo loop. This engineering parameter may be termed the *Intrinsic Natural Frequency* (*INF*) of the gear set. The gear set is part of a feedback loop and, in the system block diagram, exists as a complex variable, in which the real part of the variable represents the real gain ratio over a frequency range, and the imaginary part of the complex number represents a phase angle (lag) over the same frequency spectrum. (This statement is a simplification of the exact facts, but is adequate for the present discussion.)

Any feedback loop will go into unstable oscillation if the total lag around the loop equals or exceeds 180 deg when the loop gain is unity or greater.

Any lag angle or time delay in the gear sets must obviously be deducted from this 180-deg total and, to that extent, decreases the allowable lag for other portions of the system. Thus, the amount of lag angle which the gear box contributes to system operation is the system design parameter of paramount interest.

The present point of interest is that *INF* is an inverse (though not linear) parameter of lag. The statement can be made unequivocally that, of two otherwise physically identical gear sets, the one having the highest *INF* will give the best and most acceptable servo performance. The *INF* of a gear set may be readily calculated and is subject to shop check and verification, after certain shop and design "fudge factors" are inserted.

How can it be possible to ascertain in advance the performance of a gear set in a complex system? Rigorously, of course, the problem is not nearly so clear-cut and straightforward as indicated. Nevertheless, the practicability and feasibility of using *INF* as a design parameter can be realized by reference to several familiar concepts in the field of energy application and transformation:

1. If the internal impedance of a power supply is low relative to its load, power transfer to the load is easy and certain, and vice versa. (Compare the impedances of storage batteries and vacuum tubes as power sources.)
2. The electronic-circuit designer, when striving for high stability, tries to arrange circuits so that the internal impedance of a circuit seen from the output terminals is much lower than the input impedance of the driven circuit.

In order to justify these statements, consider the following facts:

Fact I. Most of the effective compliance appearing at the servo input shaft is actually caused by elastic deformation at the output shaft. For instance, if the output pinion is locked in a fixture similar to that shown in Fig. 8, and the torsional compliance (= 1/torsional spring constant) is measured in a fixture such as that illustrated in Fig. 9, it can be readily ascertained by test that the slope of the torsional stress-strain curve on the input shaft is equal to the square of the gear ratio times the output compliance. Symbolically,

$$C_i = R_{i_1}^2 C_{o_1} + R_{i_2}^2 C_{o_2} + \cdots R_{i_j}^2 C_{o_n} = \sum_{j=1}^{j=n} R_{i_j}^2 C_{o_j} \tag{1}$$

where

C_i = input compliance $= \dfrac{1}{K_i}$

K_i = input spring constant

C_o = output compliance $= \dfrac{1}{K_o}$

K_o = output spring constant

C_{o_j} = jth output compliance

R_{i_j} = gear ratio with respect to input shaft of the jth output compliance

The output compliance C_o can be computed by adding the different compliances of the gear-box elements, such as tooth bending, shaft bending, bearing deflections, etc.

A linear spring constant K_L may be transferred to a circular-spring-constant basis by multiplying by the square of the distance to the axis of rotation:

$$K_o = K_L D^2 \tag{2}$$

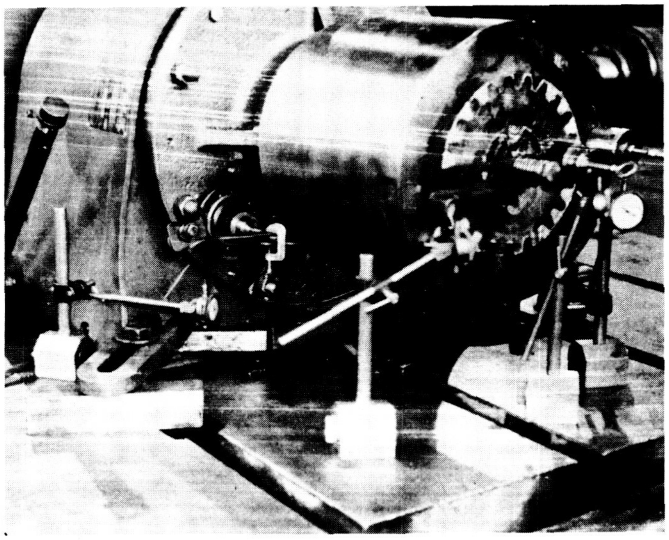


Fig. 8. Test fixture for determination of output spring constant (Falk Corporation factory)

where

K_o = circular spring constant resulting from linear bending of an element

K_L = linear spring constant of element

D = distance from axis of rotation of K_L

Fact II. Most of the inertia-energy storage of a gear box occurs at the input end, because this is the high-speed zone. Since inertia appearing at the input end due to output members must be divided by the square of the gear ratio, the output members usually contribute very little to the effective input inertia that acts as a load on the servo drives. This fact may be expressed as

$$j_i = j'_i + \frac{j''}{R_i''^2} + \frac{j'''}{R_i'''^2} \cdots = \Sigma \frac{j'}{R_i^2} \tag{3}$$

where

j = inertias at various gear positions

j_i = inertia at input

Primes = different sources of inertia

R_i = gear ratio with respect to input shaft

We thus draw the fundamental conclusion: *The Intrinsic Natural Frequency of the gear box is the equivalent spring mass frequency of the effective input inertia resonated against the equivalent output spring constant transferred to the input shaft.* Or, stated mathematically,

$$INF = \frac{1}{2\pi}\sqrt{\frac{K_i}{j_i}} \tag{4}$$

It is important to specify the exact compliances included in K_i: i.e., whether K_i is computed from data obtained in test-fixtures similar to those shown in Figs. 8 and 9, or also includes pinion-tooth, shaft, and bearing deflections, or, finally, gear-system and mounting deflections.

Equations 1 and 3 may be inserted in Eq. 4 to obtain the following expression:

$$INF = \frac{1}{2\pi}\sqrt{\frac{1}{j_i \times C_i}} = \frac{1}{2\pi}\sqrt{\frac{1}{\Sigma_j j_{i_j} \times \Sigma R_i^2 C_{o_j}}} \tag{5}$$

In many cases, serious error will not result from use of the following simplification:

$$INF \sim \frac{1}{2\pi R_i}\sqrt{\frac{K_o}{j_i}} \tag{6}$$

The parameter INF can be measured in the laboratory by locking the output shaft in some standard reproducible manner and applying torque to the input shaft by means of a horizontal gravity-driven simple pendulum of j_i inertia (Fig. 10). To obtain INF_{meas}, pluck the horizontal pendulum and measure the frequency with which it oscillates. Thus,

$$INF_{meas} = \frac{1}{2\pi R_i}\sqrt{\frac{K_o}{2j_i}} \cong \frac{INF}{\sqrt{2}} \tag{7}$$

$$INF \cong INF_{meas} \times \sqrt{2} \tag{8}$$

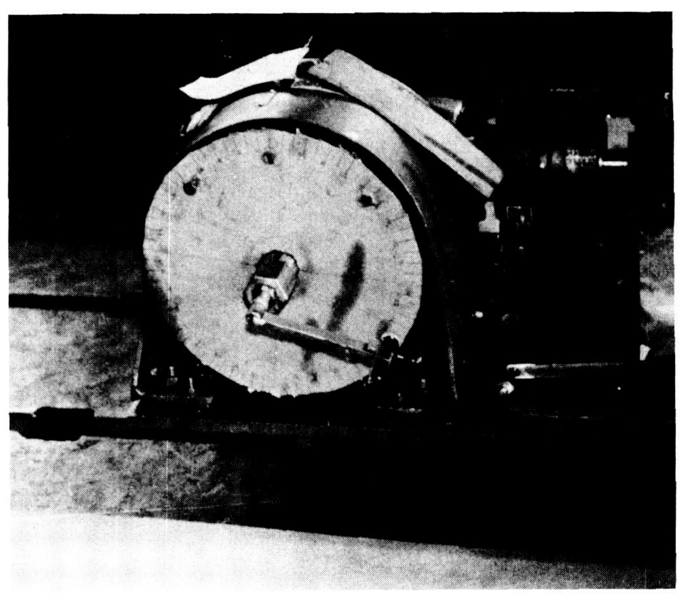


Fig. 9. Test fixture for determination of input compliance (Falk Corporation factory)

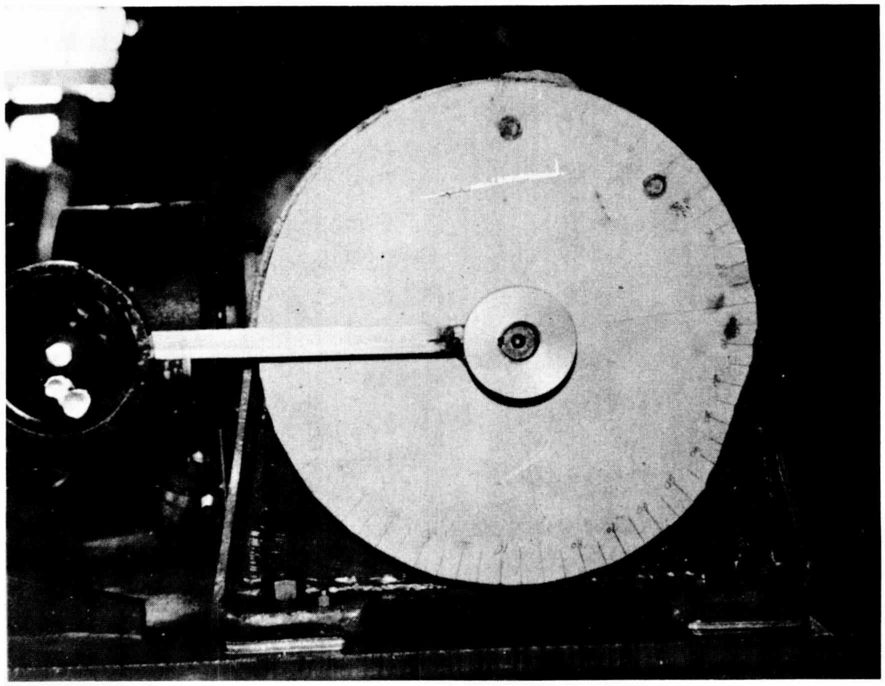


Fig. 10. Pendulum test fixture for determination of INF_{meas} (Falk Corporation factory)

V. SUMMARY

To summarize, a large servo gear drive should have high output stiffness, low input compliance, and low input inertia. These design parameters conveniently combine into one criterion parameter *INF*, the *Intrinsic Natural Frequency*, which can be used to monitor design of the gear system and components.

The Laboratory's Goldstone test program has shown that good conventional gearing practice, in itself, is not sufficient to assure 100-percent successful operation. Additional testing and, if necessary, after-design modification of the gears is required. The DSIF antennas display satisfactory performance using state-of-the-art gearing, with reasonable optimization based on some of the techniques suggested herein. Figure 11 presents the results of a comprehensive running friction- and back-driving-torque measurement, producing data of value in servo-system analysis. The no-load back-driving torque was measured by Western Gear Corporation in the test fixture shown in Fig. 12.

The Ha-Dec antennas represent Class B stiffness/dollar ranking; the Az-El configuration represents Class C ranking. Either as a result of, or as the cause for, these configuration rankings, the Ha-Dec antennas are operating with gears of original design, upgraded in alloy content for greater strength and wear. The Az-El antenna has undergone two drive-gear modifications, one for strength, and one for stiffness. A dynamics test of the Az-El antenna at Goldstone Tracking Station is shown in Fig. 13.

Equation 6 is highly instructive to system designers. Its basic accuracy has been proven by hundreds of successful machine tools. Basically, this Equation states the fact that, after a reasonable output drive stiffness is achieved (or, in system parlance, "This gear cost is prohibitive; more funds cannot be allotted for larger, more accurate gears."), the only two avenues to improvement in drive-system performance within the domain of the gear designer are: (1) decrease input inertia, and (2) decrease gear-box ratio.

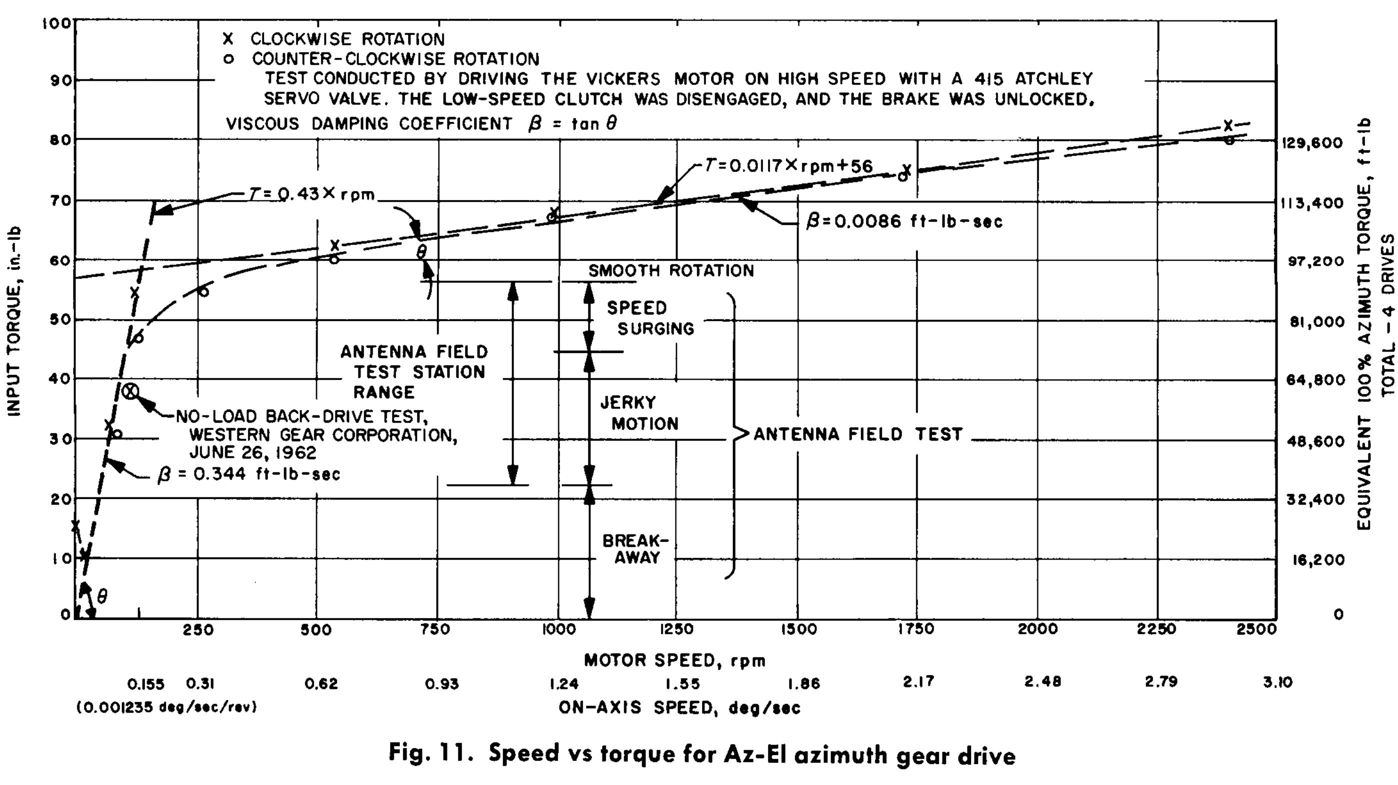


Fig. 11. Speed vs torque for Az-El azimuth gear drive

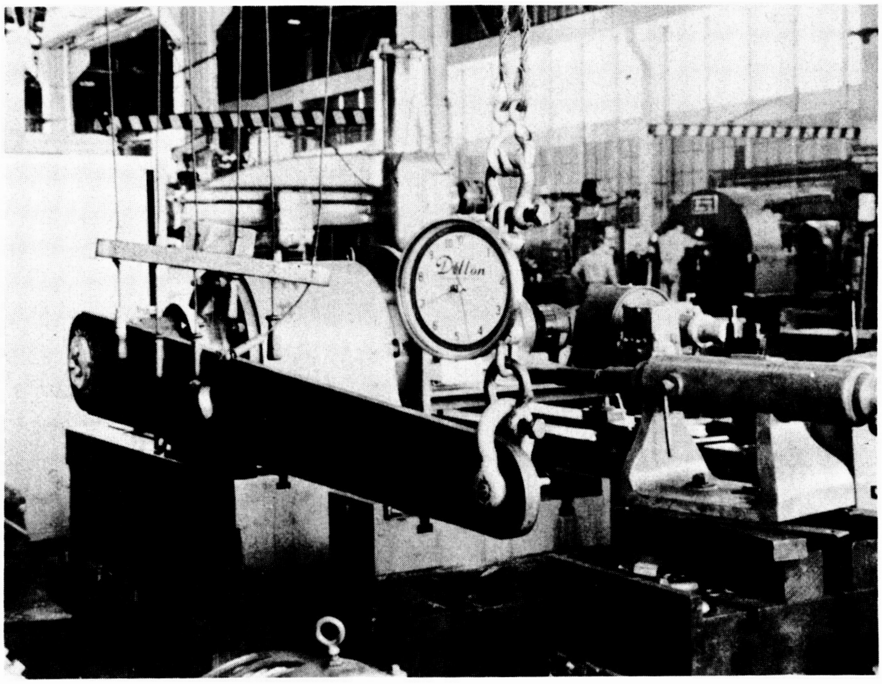


Fig. 12. Test fixture for determination of back-drive torque (Western Gear Corporation factory)

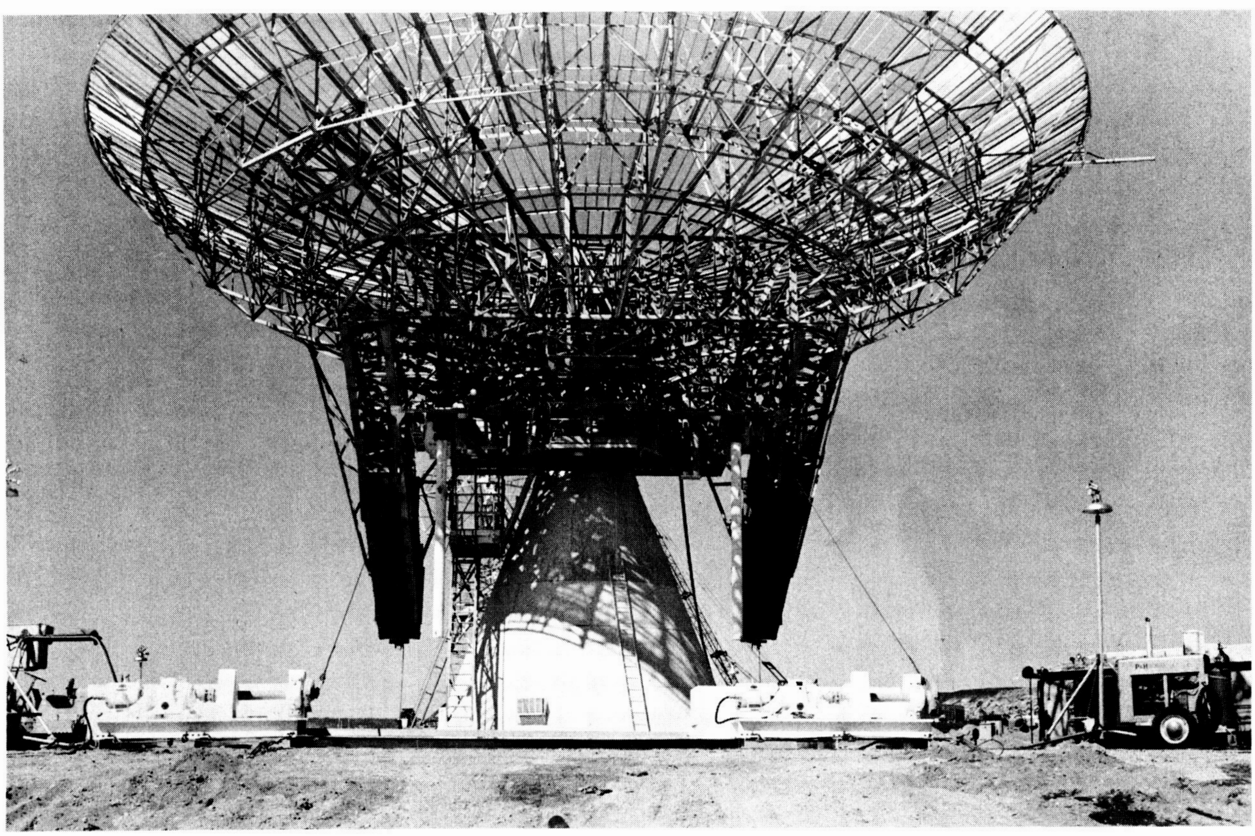


Fig. 13. Dynamics testing of Az-El antenna at Goldstone Tracking Station